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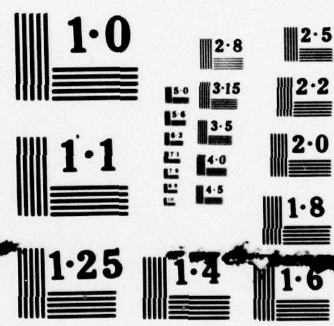


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# A RESEARCH PROGRAM IN LOGISTICS SYSTEMS

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FINAL REPORT


RICHARD L. FRANCIS
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Research was conducted on problems in facility layout, location theory, conveyor systems, scheduling and routing, inventory theory, and replacement theory. The report contains separate summaries describing the research and the principal results in each of these areas. This information is supplemented by a list of journal publications, a list of technical reports, and a list of Ph.D. degrees supported by the contract.

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## ABSTRACT

Research was conducted on problems in facility layout, location theory, conveyor systems, scheduling and routing, inventory theory, and replacement theory. The report contains separate summaries describing the research and the principal results in each of these areas. This information is supplemented by a list of journal publications, a list of technical reports, and a list of Ph.D. degrees supported by the contract.

## Facility Layout and Location Problems

Principal Investigators: R. L. Francis
T. J. Lowe

Problems were studied in a variety of areas affecting layout and location analysis. Here, we give a brief summary of these areas. Of the works discussed below, we single out as particularly substantial accomplishments the results presented in the two related papers, "Convex Location Problems on Tree Networks," and "Distance Constraints for Tree Network Multifacility Location Problems."

### Facility Layout Problems

A layout in k-dimensional Euclidean space is defined to be a collection of n non-overlapping sets. Each set is to be occupied by a specific activity (the ith set is associated with activity i), and there are measure (area) requirements for each set. If $k = 1$, the layout problem is on the line and if $k = 2$, the layout problem is in the plane.

A useful way to evaluate a layout is to associate with each activity (or set) a non-decreasing function. Given any layout, the argument of the ith function is the maximum distance between any point in the ith set and any point in any set other than the ith set. As a means of evaluating a given layout, we either measure the maximum (over i) of the function values, or we add up the function values.

In the paper "The Layout of Divisible Activities on the Line," we develop algorithms for finding layouts which minimize the maximum of the function values (minimax layout) and layouts which minimize the sum of the function values (minisum layout), for the case where $k = 1$. Insights we gain for $k = 1$ are useful for our study of problems in the plane ($k = 2$). In "Rectangular Layout Problems with Worst-Case Distance Measures," we develop algorithms for solving special rectangular cases of the minimax and minisum problems in the plane ($k = 2$).

A basic insight gained from our study of these problems is that optimal layouts display a "nesting" property in that less important activities (as measured by the functions and area requirements) nest about the most important activity.

The paper "A Minimax Facility Layout Problem Involving Distances Between and Within Facilities," presents a simple solution procedure for the problem of laying out n facilities, where each facility takes up a planar region of known area but with shape not prespecified, so as to minimize the maximum of the following terms: the greatest of the rectilinear distances between all pairs of regions; the greatest of the rectilinear distances within specified regions. The procedure for finding minimax layouts provides several qualitative insights; certain facilities of largest, and possibly second largest area, are placed so that they are not enclosed by other facilities; placing them so that they are enclosed would otherwise increase unnecessarily the distance between the enclosing facilities. To the best of our knowledge the paper presents the first provably optimal results obtained for any planar layout problem for which the objective function represents the distances between facilities, and facility shapes are not prespecified.

In the paper "On Characterizing Supremum-Efficient Facility Designs," the facility designs of interest are typically planar regions of known area but with shape not prespecified. Each facility evaluator/user i has a given disutility function, say $f_i$, so that for any facility S the disutility of S to i, denoted by $G_i(S)$, is defined to be the supremum of the disutility function $f_i$ over the region S, leading to a vector of design disutilities, $G(S) = (G_i(S))$. Supremum-efficient designs are those designs solving the resultant vector minimization problem for the set $\{G(S) : S \text{ a design}\}$. Given mild assumptions about the disutility functions, and a slight refinement of the definition of a design to rule out certain pathologies, necessary and sufficient conditions are obtained for a design to be supremum-efficient. Additional results are then obtained by invoking convexity assumptions.

A study related to layout problems appears in "The Generalized Market Area Problem"; an economic activity operating a number of plants, desires to partition the geographical space occupied by its customers into market areas (one for each plant) in order to minimize total production and transportation cost. The problem is reduced to a mathematical programming problem and an economic interpretation at the optimal solution is provided.

In the paper "A Least Total Distance Facility Configuration Problem Involving Lattice Points," facility locations are considered to be planar lattice points (e.g., squares on a checker board) and a facility configuration is a choice of any n lattice points. The problem of interest is to find facility configurations minimizing the total of the rectilinear distances between pairs of lattice points within a configuration. Properties of least total distance configurations are obtained, an implicit enumeration procedure for constructing such configurations is given, and computational results for the procedure are presented.

The paper "Some Layout Problems on the Line with Interdistance Constraints and Costs," considers some layout problems on the line (e.g., an aisle) with lower bounds on distances between adjacent facilities, and costs proportional to distances between facilities. Special problem structure is exploited to obtain efficient solution procedures which are, at worst, of quadratic order in terms of the number of facilities.

In warehouse layout problems it is necessary to know the demand for space. This interest in the demand for space led to the paper "A Greedy Algorithm for a Warehouse Leasing Problem," where we study a warehouse leasing problem where a decision maker must make decisions regarding warehouse space needed over a finite planning horizon. His demand for warehouse space is a random variable in each time period. In any period that demand exceeds his warehouse space he must obtain (at a penalty) additional warehouse space. We formulate the problem and solve it with an extremely fast and efficient (greedy) algorithm. In addition, economic interpretations are provided.

## Facility Location Problems

The primary facility location problems of interest have been location problems on networks, such as road or other transport networks, where distances between facilities are obtained by using the (shortest-path) network distances. We discuss these network location problems below.

To quote from a review of the paper "Convex Location Problems on Tree Networks," "The present paper provides new theoretical material which usefully extends and codifies much present knowledge about such problems, and provides useful guidance (some of it discouraging) for subsequent research." In this paper we establish that a large class of network location problems is convex for all choices of the data if and only if the network is a tree, and show that a number of previous algorithms for solving such problems are in fact special cases of more general algorithms for minimizing a convex function on a tree network. Also, we identify several nonconvex problems, the p-center and p-median problems in particular, which have subsequently been shown to be NP-complete by Hakimi and others. Perhaps the basic contribution of the paper is the manner in which convexity provides a unifying framework for studying location problems on tree networks. It is the only paper we know of on network location problems which provides a unifying theoretical framework, and we consider the paper to be quite a substantial contribution to the network location research literature.

Continuing the exploitation of convexity, the paper "Efficient Solutions in Multiobjective Tree Network Location Problems" involves the study of the location of a single new facility on a tree network where there are two or more non-commensurable convex functions (involving the location of the new facility) which are to be minimized. We characterize the efficient (undominated) set of solutions and provide an algorithm for determining the efficient set.

A natural outgrowth of the work on convexity in tree network location problems is the work reported in "Distance Constraints for Tree Network Multifacility Location Problems." The distance constraints, first stated in the convexity paper, are for a problem where multiple new facilities are to be located in a tree network, with respect to known existing facilities in the network and to one another, and upper bounds are imposed on distances between all pairs of such facilities. We obtain necessary and sufficient conditions, termed the separation conditions, for the distance constraints to be consistent, and give an efficient algorithm which constructs a feasible solution to the distance constraints whenever one exists. The separation conditions result is one of the most powerful single results for network location problems which we know of, and has proved to be useful subsequently in problems one might think would be unrelated to the distance constraints.

The work on distance constraints has been continued in the paper "Binding Inequalities for Tree Network Location Problems with Distance Constraints." The separation conditions consist of a family of inequalities, each of which consists of an upper bound on the network distance between a pair of existing facility locations, with the upper bound computed as a shortest path length in an auxiliary network, which in turn has as arc lengths the (upper bound) terms on the right side of the original distance constraints. In this paper we consider problems for which one or more separation condition inequalities hold as an equality; such problems are related in a natural way to having one or more distance constraints also holding as an equality, i.e., being "binding." We obtain necessary and sufficient conditions for the distance constraints to have a unique solution, and apply these and related conditions to multifacility location problems which are either minimax problems or "efficient" location problems. An interesting and unexpected result of the investigation is that the algorithm for constructing feasible solutions, given in the distance constraints paper, is an optimum algorithm, in the sense that there is no other algorithm of lower computational order for constructing feasible solutions.

In the paper "A Note on a Nonlinear Minimax Location Problem on a Tree Network," the problem is considered of locating one new facility with respect to a number of existing facilities, on a tree network. For each existing facility there is a disutility which is a strictly increasing (possibly non-linear) function of the distance between the new and existing facility, and the problem of interest is to find a new facility so that the maximum of all such costs will be minimized. Necessary and sufficient conditions for a new facility to be an optimum solution to the problem are given, as well as a procedure which can be used to compute an optimum solution. The study of the problem is motivated in part by the consideration of the problem of locating a reserve force (new facility) which may be called on to come to the support of any one of a number of forces under attack (existing facilities), when the losses of the forces under attack are strictly proportional to the travel time (or distance) between the reserve force and the attacked forces, and the reserve force is located so that its response will minimize the maximum loss.

Two other closely related location problems, not involving networks, have been studied. In the paper "Efficient Points in Location Problems," a single facility multiobjective location problem in the plane is analyzed. The idea is to find the location of a single new facility which is an "efficient" location with respect to number of existing facilities. The distance measure from the new facility to each existing facility is the rectilinear distance. A particular location is efficient when there is no other location which is simultaneously closer to all existing facilities. Two separate algorithms are presented to generate all of the efficient locations. The study provides insights into location problems where there are multiple objective functions involving distances.

The paper "Finding Efficient Solutions for Rectilinear Distance Location Problems Efficiently," considers further the problem studied in "Efficient Points in Location Problems," establishing most of the basic results using only geometry, and presenting an algorithm of lowest computational order for solving the problem.

Nonlinear Methods Applied to
Nondifferentiable Location Problems

Principal Investigator: D. W. Hearn

This research has focused on the development of algorithms for location problems which involve nondifferentiable functions. Previously, researchers had developed solution techniques which depended upon the particular type of norm (Euclidean, rectilinear, etc.) used in the problem. In our work we have developed a convergent method which is applicable to any mixture of $\ell_p$ norms. This algorithm also has important application beyond location problems because it may be used to solve piecewise linear convex optimization problems and $\ell_p$-approximation problems (generalizations of least-squares). The paper, "A Subgradient Algorithm for Certain Minimax and Minisum Problems," which describes this algorithm is forthcoming in the journal Mathematical Programming. Computational efficiency of the method is demonstrated by the solution of a variety of problems.

A recent research report, "A Feasible Direction Subgradient Algorithm for a Class of Nondifferentiable Optimization Problems," gives an extension of this algorithm to constrained problems of the same sort. It is being submitted for publication.

Finally, a heuristic algorithm for these problems which is extremely fast and easy to use has been developed and tested. The paper, "A Subgradient Procedure for the Solution of Minimax Location Problems," describing the method and comparing it with other techniques has been published in the journal, Computers and Industrial Engineering.

## Analysis of Closed-Loop Conveyor and Transportation Systems

Principal Investigator: E. J. Muth

### Introduction

The motivation for this research came from the study of closed loop-conveyor systems. The design of conveyor systems has traditionally been in the domain of industrial engineers. The operation of a closed-loop conveyor is schematically illustrated in Figure 1. Material enters the system at the loading station 1 and leaves it at the unloading station 2. The material moves from station 1 to station 2 along the forward path of the conveyor. The rate of material flow into the system and out of the system is represented by the

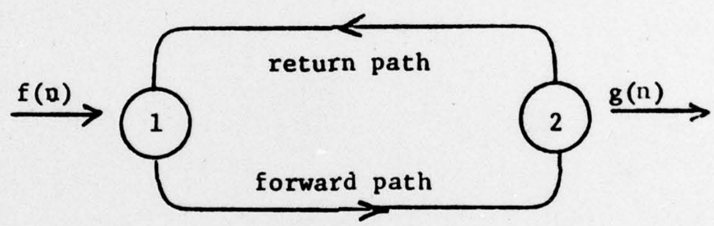


Figure 1. Closed-Loop Conveyor System

functions of time f(n) and g(n). A special feature of a closed-loop conveyor is that material may remain on the return path of the conveyor. This storage feature of the return path has a buffering effect and provides a potential for accommodating flow rates f(n) and g(n) which are not identical. A conveyor is usually a link between two manufacturing areas and thus a part of a larger system. The flow rates f(n) and g(n) are externally imposed by the overall system. Hence the conveyor may be thought of as a device which transforms the input flow f(n) into the output flow g(n).

An important question is the following. To what extent can different functions f(n) and g(n) be handled by a given conveyor without causing blocking or starving and without requiring additional storage facilities. This is an operation problem. In a similar spirit, a design problem is concerned with the question of whether a feasible design can be achieved for a specified set of functions f(n) and g(n), and if so, how the design can be optimized.

There are other fields of application for the closed-loop conveyor model. For example, the model extends to transportation systems, and to such problems as airplanes stacking up for landing at an airport, or equipments rotating through servicenters.

## Results and Conclusions

In our research we have extended previous work to include the case of systems with multiple loading and unloading stations as shown in Figure 2.

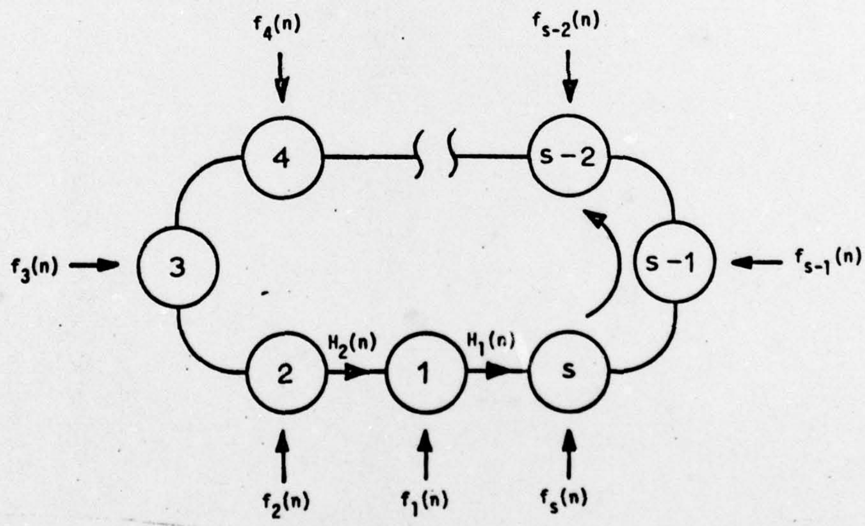


Figure 2. Multi-Station Closed-Loop Conveyor System

This model is applicable to fixed guideway transportation systems where passengers load and unload at all stations.

We feel that we have addressed an important problem and made a contribution in this area, with results reported in "Modelling and System Analysis of Multi-Station Closed-Loop Conveyors," by E. J. Muth, The International Journal of Production Research, Vol. 13, No. 6, November 1975. The important results are:

(1) A systematic procedure is provided for determining whether a specified set of flow rate functions $f_i(n)$ is compatible with a specified set of conveyor parameters.

(2) Compatibility and efficient operation depend critically on the remainder r of the quotient k/p where k is the conveyor revolution time and p is the work-cycle period. To provide greatest flexibility and compatibility for all $f_i(n)$ the ratio r/p should be a proper fraction. Conveyor compatibility is assured for all values of k if p is prime.

(3) Optimization is possible by explicit enumeration of all feasible cases.

Another extension addressed in our research is the system shown in Figure 1 where the flow rate functions are stochastic processes. Here we have been able to model the system in a novel way, with results reported in "A Model of a Closed-Loop Conveyor with Random Material Flow," by E. J. Muth, AIIE Transactions, Vol. 9, No. 4, December 1977. The most important conclusion is that a closed-loop conveyor has the capability of smoothing out random fluctuations which are present in the input flow. The ratio of the variance of the input flow to the variance of the output flow is represented by the variance reduction factor. This factor can be made arbitrarily small by providing adequate conveyor capacity.

## Scheduling and Routing in Logistics Systems

Principal Investigator: H. Donald Ratliff

The fundamental thrust of this research has been directed toward modeling scheduling and routing problems as integer programs and then characterizing within these models special structure which can be exploited to yield very efficient algorithms. We feel that we have made a major breakthrough in this area with results reported out in "Unnetworks, with Applications to Idle Time Scheduling," by Bartholdi and Ratliff, Management Science, Vol. 24, No. 8, April 1978 and "Circular 1's and Cyclic Staffing," by Bartholdi, Orlin, and Ratliff, Research Report 77-11, September 1977. The latter result has been generalized somewhat in the revised version submitted to Operations Research. In these two papers we have characterized two previously unsolved classes of integer programs which can be solved as a polynomial bounded sequence of network flow and matching problems. These integer programs have constraint matrices which are not unimodular or perfect and in fact have none of the properties which have up to now made such problems tractable. The two classes of problems include some very important scheduling and staffing problems. We feel that these results provide a promising new direction for research on structured integer programs as well as some immediately useful algorithms.

We have also developed what we believe are significant results relating location problems to minimum cut problems on an undirected graph. We have shown that a class of quadratic integer programming problems which includes the discrete rectilinear distance facility location problem and the squared Euclidean location problem can be solved as a finite and predictable sequence of minimum cut problems. These results provide new insights into location problems as well as computationally efficient algorithms. This work is reported on in "A Cut Approach to the Rectilinear Distance Facility Location Problem," by Picard and Ratliff, Operations Research, Vol. 26, No. 3, 1978 and in "A Cut Approach to a Class of Quadratic Integer Programming Problems," by Picard and Ratliff, Research Report 78-2, January 1978.

At the end of the contract period, work was underway to generalize the results on unnetworks and cyclic ones to include more general integer programming structures. If we are able to continue this work to the point where it is reported out, the ARO support will be acknowledged.

## Mathematical Modeling of Inventory and Replacement Systems, and Location Theory

Principal Investigator: B. D. Sivazlian

### Inventory Theory

Two problems were investigated.

1. The dynamic response of a multi-echelon supply chain in various demands placed upon the system by a final consumer. When each supply point in the chain uses a typical linear decision rule for placing orders, it is shown that the system amplifies minor variations in consumer demand into major disturbances at higher echelons. This amplification is traced to two sources, one being a legitimate and unavoidable inventory adjustment and the other being an unwarranted false order effect. A new decision rule is derived which automatically suppresses these false orders. The two decision rules are compared in a three-echelon simulation model, and the revised rule experienced fewer stockouts, maintained lower average inventory, and greatly reduced the amplification effect.

2. The analysis for computing probability of shortages in a periodic review multicommodity inventory system operating under a ($\sigma$, S) policy. Demands for the commodities in each period are independently and Erlang distributed. Replenishment for the commodities is made from a single source with an unlimited supply. Whenever the sum of the scaled inventories of all commodities at the end of a period reaches or drops below a "reorder" level, the inventory of commodity i, $i = 1, 2, \ldots, n$, is brought up to $S_i > 0$, otherwise nothing is ordered.

   The analysis for determining steady state probability of shortages relies on the development of an F-equation to structure a polynomial function as well as on a new recursive technique for partial fraction expansion.

The final probability expressions are compactly exhibited for numerical computations using the double dot tensorial notation.

Replacement Theory

Two problems in periodic review single and multi-component age replacement systems were studied.

1. <u>The dyadic age-replacement for a single-component system.</u>

Here the amount of deterioration over successive periods form a sequence of i.i.d. random variables. A replacement policy of the dyadic type is in effect whereby the used equipment item is discarded and immediately replaced by a new identical equipment item if at the end of a period the old equipment has service aged by an amount in excess of S or has been in operation for exactly N periods whichever comes first. Expressions for the joint distribution of the service age and the chronological age and for the distribution of the total number of replacements $N_t$ are derived. The derivation of the distribution function of $N_t$ relies on the solution to a system of linear Diophantine equations. Finally, using as criterion the minimization of the total steady-state expected cost per period, consisting of a fixed replacement cost and a linear cost of operation, optimal values of S and N are computed for a few numerical examples.

2. <u>The group replacement for a multi-component system.</u>

The stationary characteristics of an n-component periodic review system which is subject to stochastic deterioration (but not to failure) are investigated. When the n-component vector which expresses the state of deterioration of the system pierces a certain surface the entire multi-component system is replaced by items of identical cost structure at the time of the next review. In the absence of this situation nothing is replaced. It is assumed that there is a fixed cost associated with each replacement and that the operating cost of each item is a strictly increasing function of its state of deterioration. The conditions for minimizing the long-term cost of maintaining a system which operates under the stated policy were found through solution of a problem in variational calculus. Two examples are worked. A useful graph which aids in the solution of such problems is provided.

## Location Theory

The problem of maximum likelihood and optimum location of observation sites in geodetic and spatial surveying was investigated. In geodetic and spatial surveying, accurate statistical estimates of the Cartesian coordinates of a stationary target depend, in general, on such factors as target position, number and type of instruments, their location, their accuracy, and their mix. Direct measurements are assumed to be made in elevation, azimuth, and range with errors independently and normally distributed. For a mix of instruments, theoretical arguments are established using maximum likelihood estimation to determine the optimal siting of the instruments which minimizes $(GDOP)^2$ or the square of the geometric dilution of precision = sum of the variances of the estimates in the three orthogonal directions.

## JOURNAL PUBLICATIONS

| | | |
|---|---|---|
| Published Papers | Nos. | 1 - 25 |
| Accepted Papers | Nos. | 26 - 33 |
| Submitted Papers | Nos. | 34 - 46 |

1. "Minimum Cuts and Related Problems," Jean-Claude Picard and H. Donald Ratliff, Networks, Vol. 5, No. 4, 1975.

2. "A Minimax Facility Layout Problem Involving Distances Within and Between Facilities," Richard L. Francis, John J. Bartholdi, and Robert L. Papineau, AIIE Transactions, Vol. 7, No. 4, 1975.

3. "Modelling and System Analysis of Multistation Closed-Loop Conveyors," Eginhard J. Muth, Int. J. Prod. Res., Vol. 13, No. 6, November 1975.

4. "A Survey of the State of the Art in Dynamic Programming," M. E. Thomas, AIIE Transactions, March, 1976.

5. "The Generalized Market Area Problem," Timothy J. Lowe and A. P. Hurter, Jr., Management Science, June 1976.

6. "A Least Total Distance Facility Configuration Problem Involving Lattice Points," A. W. Chan and R. L. Francis, Management Science, Vol. 22, No. 7, 1976.

7. "Convex Location Problems on Tree Networks," P. M. Dearing, R. L. Francis, T. J. Lowe, Operations Research, Vol. 24, No. 4, 1976.

8. "Minimax Multifacility Location with Euclidean Distancs," Jack Elzinga, Donald Hearn, and W. D. Randolph, Transportation Science, Vol. 10, No. 4, November 1976.

9. "Reliability Models with Positive Memory Derived from the Mean Residual Life Function," E. J. Muth, The Theory and Applications of Reliability, Vol. II, Academic Press, New York, 1977.

10. "A Rectilinear Distance Round-Trip Location Problem," A. W. Chan and D. W. Hearn, Transportation Science, Vol. 11, No. 2, May 1977.

11. "Numerical Methods Applicable to a Production Line with Stochastic Servers," Eginhard J. Muth, TIMS Studies in Management Sciences, Vol. 7, 1977.

12. "A Note on a Nonlinear Minimax Location Problem on a Tree Network," Richard L. Francis, Journal of Research - National Bureau of Standards, Vol. 82, No. 1, July-August 1977.

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14. "Efficient Points in Location Problems," Timothy J. Lowe, A. P. Hurter, and R. E. Wendell, AIIE Transactions, Vol. 9, No. 3, September 1977.

15. "Scheduling Rules for Parallel Processors," H. Donald Ratliff and Louis A. Martin-Vega, AIIE Transactions, Vol. 9, No. 4, December 1977.

16. "A Model of a Closed-Loop Conveyor with Random Material Flow," Eginhard J. Muth, AIIE Transactions, Vol. 9, No. 4, December 1977.

17. "A Subgradient Procedure for the Solution of Minimax Location Problems," Donald W. Hearn and Timothy J. Lowe, Computers and Industrial Engineering, Vol. 2, January 1978.

18. "The Layout of Divisible Activities on the Line," Timothy J. Lowe, V. Darryl Thornton, and Richard L. Francis, AIIE Transactions, Vol. 10, No. 1, March 1978.

19. "Network Models for Production Scheduling Problems with Convex Cost and Batch Processing," H. D. Ratliff, AIIE Transactions, Vol. 10, No. 1, March 1978.

20. "Unnetworks, with Applications to Idle Time Scheduling," J. J. Bartholdi and H. D. Ratliff, Management Science, Vol. 24, No. 8, April 1978.

21. "Distance Constraints for Tree Network Multifacility Location Problems," Richard L. Francis, Timothy J. Lowe, and H. Donald Ratliff, Operations Research, Vol. 26, No. 4, July-August 1978.

22. "Efficient Solutions in Multiobjective Tree Network Location Problems" T. J. Lowe, Transportation Science, Vol. 12, No. 4, 1978.

23. "A Cut Approach to the Rectilinear Distance Facility Location Problem," Jean-Claude Picard and H. D. Ratliff, Operations Research, Vol. 26, No. 3, 1978.

24. "A Class of Stationary EOQ Problems and Learning Effects," E. J. Muth with K. Spremann, Lecture Notes in Economics and Mathematical Systems, Vol. 157, Springer Verlag, Berlin, 1978.

25. "Minimization of Time-Varying Costs in Single-Machine Scheduling," B. D. Sivazlian and E. L. Lawler, Operations Research, Vol. 26, No. 4, July-August 1978.

26. "Some Layout Problems on the Line with Interdistance Constraints and Costs," Albert W. Chan and Richard L. Francis, accepted by Operations Research.

27. "Efficient Solutions in Multiobjective Tree Network Location Problems," T. J. Lowe, accepted by Transportation Science.

28. "A Subgradient Algorithm for Certain Minimax and Minisum Problems," Timothy J. Lowe, Donald W. Hearn, and Jacques Chatelon, accepted by Mathematical Programming.

29. "A Method for Determining the Autocovariance Function of a Box-Jenkins Forecasting Model," E. J. Muth, accepted by AIIE Transactions.

30. "The Reversibility Property of Production Lines," E. J. Muth, accepted by Management Science.

31. "Maximum Likelihood and Optimum Location of Observation Sites in Geodetic and Spatial Surveying," B. D. Sivazlian, accepted by Communications in Statistics.

32. "Group Replacement of a Multi-Component System Which is Subject to Deterioration Only," B. D. Sivazlian and J. F. Mahoney, accepted by Advances in Applied Probability.

33. "Dynamic Analysis of Multi-Echelon Supply Systems," B. D. Sivazlian and J. F. Burns, accepted by Computers and Industrial Engineering.

34. "Circular 1's and Cyclic Staffing," John J. Bartholdi, James B. Orlin, and H. Donald Ratliff, submitted to Operations Research.

35. "Finding Efficient Solutions for Rectilinear Distance Location Problems Efficiently," Luc G. Chalmet and Richard L. Francis, submitted to AIIE Transactions.

36. "On Characterizing Efficient Supremum-Efficient Facility Designs," Luc G. Chalmet, Richard L. Francis, and James F. Lawrence, submitted to Mathematics of Operations Research.

37. "Rectangular Layout Problems with Worst-Case Distance Measures," V. D. Thornton, R. L. Francis, and T. J. Lowe, submitted to AIIE Transactions.

38. "Binding Inequalities for Tree Network Location Problems with Distance Constraints," Richard L. Francis, Timothy J. Lowe, and Barbaros C. Tansel, submitted to Transportation Science.

39. "A Greedy Algorithm for a Warehouse Leasing Problem," T. J. Lowe, R. L. Francis, and E. W. Reinhardt, submitted to AIIE Transactions.

40. "Observations on the Minimum Sphere Problem," Donald Hearn, submitted to Naval Research Logistics Quarterly.

41. "Computation of Probability of Shortages in a Multicommunity ($\sigma$, S) Inventory Problem with Erlang Distributed Demands," J. F. Mahoney and B. D. Sivazlian, submitted to Management Sciences.

42. "Scheduling Rules for a Class of Fixed Route Freight Scheduling Problems," Louis A. Martin-Vega and H. D. Ratliff, submitted to Management Science.

43. "Conveyor Theory: A Survey," Eginhard J. Muth and John A. White, submitted to AIIE Transactions.

44. "Unimodular and Totally Unimodular Matrices," H. Donald Ratliff and John J. Bartholdi, submitted to Mathematical Programming.

45. "A Cut Approach to a Class of Quadratic Integer Programming Problems," Jean-Claude Picard and H. Donald Ratliff, submitted to Networks.

46. "A Dyadic Age-Replacement Policy for a Periodically Inspected Equipment Item Subject to Random Deterioration," B. D. Sivazlian and Srinivas N. Iyer, submitted to Management Sciences.

## RESEARCH REPORTS

1. "Families of Distribution with Positive Memory Derived from the Mean Residual Life Function," Eginhard J. Muth (October, 1975).

2. "A Cut Approach to the Rectilinear Distance Facility Location Problem," Jean-Claude Picard and H. Donald Ratliff (December, 1975).

3. "Distance Constraints for Tree Network Multifacility Location Problems," Richard L. Francis, Timothy J. Lowe, and H. Donald Ratliff (February, 1976).

4. "Efficient Solutions in Multiobjective Tree Network Location Problems," Timothy J. Lowe (March, 1976).

5. "A Subgradient Procedure for the Solution of Minimax Location Problems," Donald Hearn and T. J. Lowe (March, 1976).

6. "Numerical Methods Applicable to a Production Line with Stochastic Servers," Eginhard J. Muth (May, 1976).

7. "The Layout of Divisible Activities on the Line," Timothy J. Lowe, V. Darryl Thornton, and Richard L. Francis (April, 1976).

8. "Scheduling Rules for Parallel Processors," Louis A. Martin-Vega and H. Donald Ratliff (May, 1976).

9. "Effect of Mixed Instrumentation in Tracking Targets with Minimal Error," B. D. Sivazlian (May, 1976).

10. "An Algorithm for Mixed Norm Minimax Location Problems," Jacques Chatelon, Donald Hearn, and Timothy J. Lowe (June, 1976).

11. "Efficient Network Solutions to Parallel Processor Scheduling Problems: A Survey," John J. Bartholdi, Louis Martin-Vega, and H. Donald Ratliff, (June, 1976).

12. "Permutation Type Schedules on a Single Machine Under Cost Criteria," B. D. Sivazlian (July, 1976).

13. "Network Models for Production Scheduling Problems with Convex Cost and Batch Processing," H. Donald Ratliff (August, 1976).

14. "Efficient Points in Location Problems," Richard E. Wendell, Arthur P. Hurter, and Timothy J. Lowe (July, 1976).

15 "A Method for Determining the Autocovariance Function of a Box-Jenkins Forecasting Method," Eginhard J. Muth (August, 1976).

16. "Unimodular and Totally Unimodular Matrices," John J. Bartholdi and H. Donald Ratliff (August, 1976).

17. "A Model of a Closed-Loop Conveyor with Random Material Flow," Eginhard J. Muth (September, 1976),

18. "A Note on a Nonlinear Minimax Location Problem on a Tree Network," Richard L. Francis (October, 1976).

19. "The Incomplete Dirichlet's Multiple Integral," B. D. Sivazlian (November, 1976).

20. "A Subgradient Algorithm for Certain Minimax and Minisum Problems," Jacques Chatelon, Donald Hearn, and Timothy J. Lowe (January, 1977).

21. "Finding Efficient Solutions for Rectilinear Distance Location Problems Efficiently," Luc G. Chalmet and Richard L. Francis (March, 1977).

22. "Unnetworks, with Applications to Idle Time Scheduling," John J. Bartholdi and H. Donald Ratliff (April, 1977).

23. "Observations on the Minimum Sphere Problem," Donald Hearn (May, 1977).

24. "A Dyadic Age-Replacement Policy for a Periodically Inspected Equipment Item Subject to Random Deterioration," Srinivas N. Iyer and B. D. Sivazlian (July, 1977).

25. "Rectangular Layout Problems with Worth-Case Distance Measures," V. Darryl Thornton, Richard L. Francis, and Timothy J. Lowe (August, 1977).

26. "Circular 1's and Cyclic Staffing," John J. Bartholdi, James B. Orlin, and H. Donald Ratliff (September, 1977).

27. "A Greedy Algorithm for a Warehouse Leasing Problem," Timothy J. Lowe, Richard L. Francis, and Eric W. Reinhardt (October, 1977).

28. "Group Replacement of a Multicomponent System Which is Subject to Deterioration Only," B. D. Sivazlian and J. F. Mahoney (October, 1977).

29. "The Reversibility Property of Production Lines," E. J. Muth, (January, 1978).

30. "A Cut Approach to a Class of Quadratic Integer Programming Problems," Jean-Claude Picard and H. Donald Ratliff, (January, 1978).

31. "The Autocovariance Function Determined Via the Z-Transform, with Application to Box-Jenkins Forecasting Models," Eginhard J. Muth, (May, 1978).

32. "On Characterizing Efficient Supremum-Efficient Facility Designs," Luc G. Chalmet, Richard L. Francis, and James F. Lawrence (June, 1978).

33. "Binding Inequalities for Tree Network Location Problems with Distance Constraints," Richard L. Francis, Timothy J. Lowe, Barbaros C. Tansel (August, 1978).

34. "Efficiency in Integral Facility Design Problems," Luc G. Chalmet, Richard L. Francis, and James F. Lawrence (August, 1978).

35. "A Feasible Direction Subgradient Algorithm for a Class of Nondifferentiable Optimization Problems, Jacques Chatelon, Donald Hearn, and Timothy J. Lowe (October, 1978).

## Ph.D. DEGREES

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1. J. A. Chatelon, March 1977, "Subgradient Algorithm for Certain Minimax and Minisum Problems."

2. K. T. Nguyen, June 1977, "Models for Hospital Census Prediction and Allocation."

3. J. J. Bartholdi, August 1977, "Scheduling Via Networks, Unnetworks, and Almost Networks."